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ORIGINAL ARTICLE

# Decreasing dimensions of planar field-effect transistors by using native inhomogeneity of heterostructure

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**Abstract** In this paper we consider an approach to decrease dimensions of planar field-effect transistors in a semiconductor heterostructure. Some recommendations have been formulated to optimize technological processes in order to maximize the decreasing of the dimensions of the transistor.

**Keywords** Planar field-effect transistors · Decreasing dimensions of transistors · Transistors in heterostructure

## Introduction

In order to decrease the dimensions of elements of integrated circuits (such as *p–n* junctions and transistors) some approaches have been elaborated (Lachin and Savelov 2001; Grebene 1983; Gotra 1991; Ong et al. 2006; Ahlgren et al. 1997; Kerentsev and Lanin 2008). One of them is formation of inhomogenous distribution of temperature (by using laser or microwave annealing) (Ong et al. 2006; Sundaresan 2007; Bykov et al. 2003). It could be also attracted an interest to use inhomogenous distribution of defects (Kozlivsky 2003). Another way to decrease dimensions of the devices (discrete devices and elements of integrated circuits) is optimization of technological process. Framework this way we consider a possibility to decrease dimensions (increasing of density of elements of integrated circuits and decreasing of depth of devices) of planar field-effect transistors.

## Statement of the problem

Let us consider a heterostructure (H). The H consist of a substrate (S) with known type of conductivity (*n* or *p*) and two epitaxial layers (ELs) with some insertions, which consist of another materials (see Fig. 1). In the insertions the ELs one or two dopants (depends on quantity of the insertions) have been infused. Further a layer of oxide and contacts are have been manufactured (see Fig. 2). Profile of side elevation drawing of the obtained structure is presented in Fig. 2. Figures 3 and 4 are illustrated relations between initial distributions of dopant and structure of H in neighborhood of contacts. It has been recently shown (see, for example, Pankratov 2005, 2010), that optimization of annealing time gives us possibility to manufacturing a *p–n* junction with higher sharpness and higher homogeneity of dopant distribution near appropriate interface between layers of H. Main aims of the present paper are modification of structure of planar field-effect transistor and optimization of annealing time to manufacturing more compact field-effect transistors.

## Method of solution

To solve our aims let us determine spatiotemporal distribution of dopant concentration. We determine the distribution by solving the second Fick's law (Lachin and Savelov 2001; Grebene 1983; Gotra 1991)

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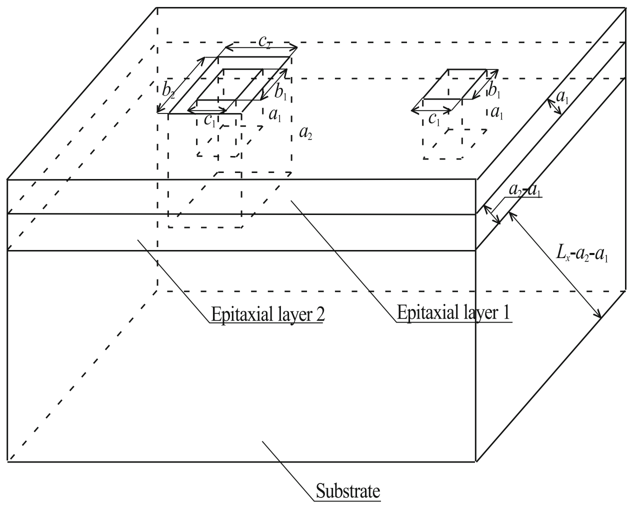


**Fig. 1** Heterostructure with two epitaxial layers. Nearest to the substrate epitaxial layer, includes into itself one part of another material, which has been inserted by etching to the substrate and overgrowth of the open “window”. The second epitaxial layer has three analogous parts, which has been inserted by the same technological steps from free surface of the epitaxial layer to another epitaxial layer or substrate. Dimensions of the inserted parts are shown in the figure:

$$\frac{\partial C(x,y,z,t)}{\partial t} = \frac{\partial}{\partial x}\left[D_{\mathrm{C}}\frac{\partial C(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_{\mathrm{C}}\frac{\partial C(x,y,z,t)}{\partial y}\right] + \frac{\partial}{\partial z}\left[D_{\mathrm{C}}\frac{\partial C(x,y,z,t)}{\partial z}\right] \tag{1}$$

with boundary and initial conditions

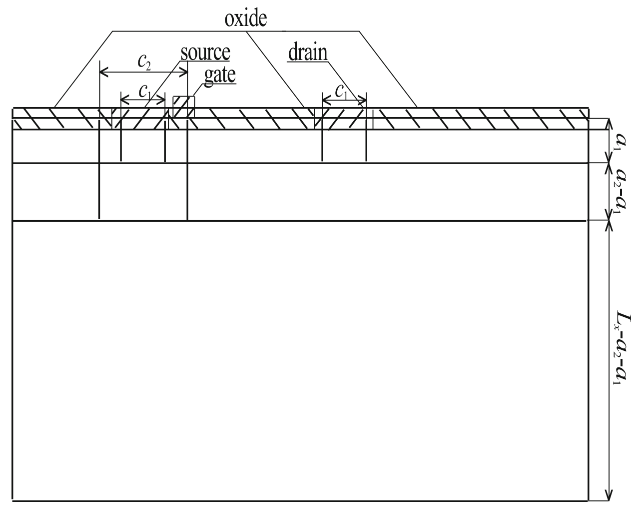


**Fig. 2** In this figure, heterostructure from Fig. 1 is shown from one side

Here $P(x, y, z, T)$ is the limit of solubility of dopant in H; $D_{\mathrm{L}}(x, y, z, T)$ is the diffusion coefficients for low-level of doping; parameter $\gamma$ depends on properties of materials of H and could be integer usually in the interval $\gamma \in [1, 3]$ (Gotra 1991); $T$ is the temperature of annealing. Dopant diffusion coefficient depends on temperature due to Arrhenius law. Due to the law we can take into account inhomogenous distribution of temperature for consideration laser or microwave annealing.

Let us determine spatiotemporal distribution of dopant concentration by using recently introduces approach (Pankratov 2005). Framework the approach we transform

$$\left.\frac{\partial C(x,y,z,t)}{\partial x}\right|_{x=0} = 0, \left.\frac{\partial C(x,y,z,t)}{\partial x}\right|_{x=L_x} = 0, \left.\frac{\partial C(x,y,z,t)}{\partial y}\right|_{y=0} = 0, \left.\frac{\partial C(x,y,z,t)}{\partial y}\right|_{y=L_y} = 0,$$
$$\left.\frac{\partial C(x,y,z,t)}{\partial z}\right|_{z=0} = 0, \left.\frac{\partial C(x,y,z,t)}{\partial z}\right|_{z=L_z} = 0, \quad C(x,y,z,0) = f_C(x,y,z). \tag{2}$$

Here $C(x, y, z, t)$ is the spatiotemporal distribution of dopant concentration; $D_{\mathrm{c}}$ is the diffusion coefficient of dopant. Value of dopant diffusion coefficient depends on properties of materials of layers in H, on rate of heating and cooling of H and on spatiotemporal distribution of dopant concentration. Concentrational dependence of diffusion coefficient could be approximated by the following function (Gotra 1991)

$$D_{\mathrm{C}} = D_{\mathrm{L}}(x,y,z,T)\left[1 + \xi\frac{C^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\right]. \tag{3}$$

approximation of dopant diffusion coefficient to the following form: $D_{\mathrm{L}}(x,y,z,T) = D_{0L}[1 + \epsilon g_{\mathrm{L}}(x,y,z,T)]$, where $D_{0L}$ is the average value of diffusion coefficient. Further we determine solution of the Eq. (1) as the following power series

$$C(x,y,z,t) = \sum_{i=0}^{\infty}\epsilon^{i}\sum_{j=0}^{\infty}\xi^{j}C_{ij}(x,y,z,t).$$

Substitution of the series in the Eqs. (1) and (2) gives us possibility to obtain equations for zero-order approximation

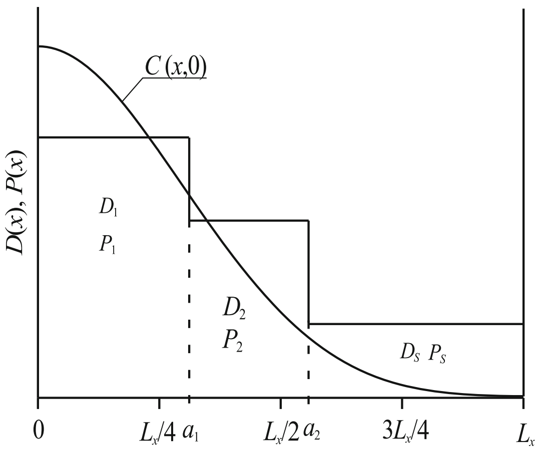


**Fig. 3** Dependences of dopant diffusion coefficient and limit of solubility on coordinate $x$ through heterostructure from drain to substrate. The *figure* also shown initial distribution of infused dopant near drain. $D_i$ and $P_i$ are values of dopant diffusion coefficient and limit of solubility in layers of heterostructure

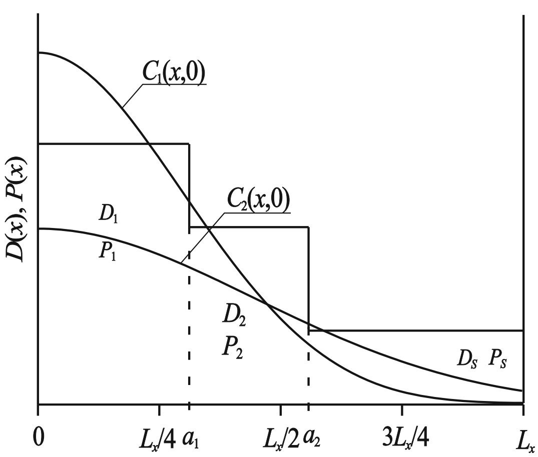


**Fig. 4** Dependences of dopant diffusion coefficients and limits of solubility on coordinate $x$ through heterostructure from drain to substrate. The *figure* also shown initial distributions of infused dopants near source. $D_i$ and $P_i$ are values of dopant diffusion coefficients and limits of solubility in layers of heterostructure

of dopant concentration $C_{00}(x, y, z, t)$, corrections to it $C_{ij}(x, y, z, t)$ and boundary and initial conditions to them. The equations and conditions for them are presented in the Appendix. It should be noted, that the series on the parameter $\epsilon$ will be always convergence due to positively of dopant diffusion coefficient.

Analysis of spatiotemporal distributions of dopant concentrations has been done analytically by using the second-order approximation of dopant concentration. Farther the distribution has been amended numerically.

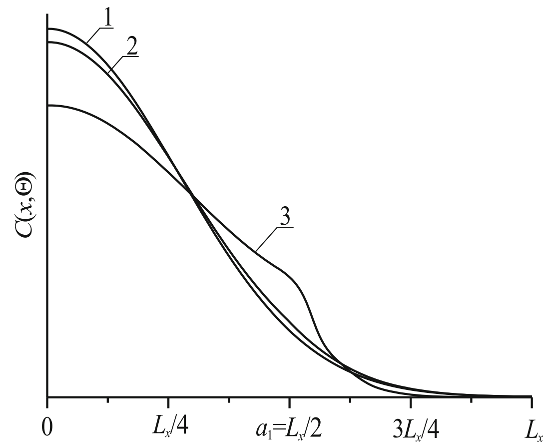


**Fig. 5** Distribution of dopant in heterostructures with two layers (substrate and one epitaxial layer) for different values of difference between dopant diffusion coefficients in layers of the heterostructures. *Curve1* corresponds to equal to each other valuers of dopant diffusion coefficients ($D_1/D_S = 1$). *Curve 2* corresponds to small difference between values of dopant diffusion coefficients ($D_1/D_S = 1.2$). *Curve 3* corresponds to large difference values of dopant diffusion coefficients ($D_1/D_S = 9$)

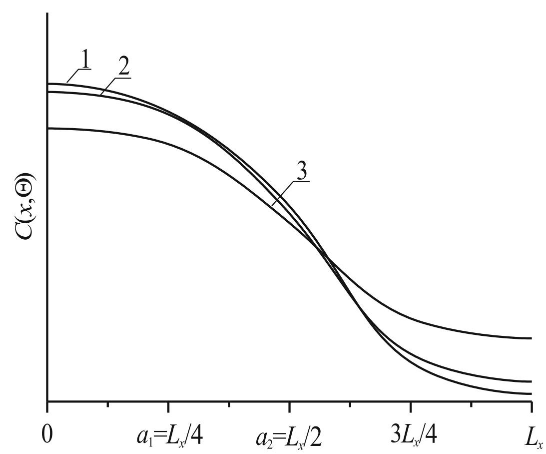


**Fig. 6** Distribution of dopant in heterostructures with three layers (substrate and two epitaxial layers) for different values of difference between dopant diffusion coefficients. *Curve 1* corresponds to equal to each other values of dopant diffusion coefficients ($D_1/D_2 = D_2/D_S = 1$). *Curve 2* corresponds to small difference between values of dopant diffusion coefficients ($D_1/D_2 = D_2/D_S = 1.2$). *Curve 3* corresponds to average difference values of dopant diffusion coefficients ($D_1/D_2 = D_2/D_S = 3$)

## Discussion

Let us consider spatial distribution of dopant for different values of difference between diffusion coefficients in layers of H and annealing of time. Some spatial distributions of concentration of dopant are presented in Figs. 5, 6, 7, 8 for different values of difference between dopant diffusion

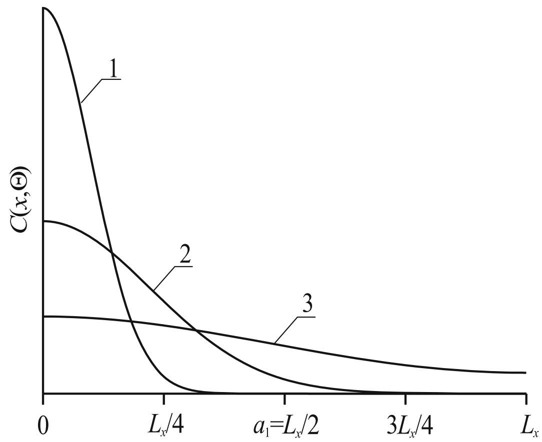


**Fig. 7** Distribution of dopant in heterostructure with two layers (substrate and one epitaxial layer) for different values of annealing time. Values of annealing time are: $\Theta = 0.01\,L^2/D_0$, $\Theta = 0.1\,L^2/D_0$ and $\Theta = L^2/D_0$

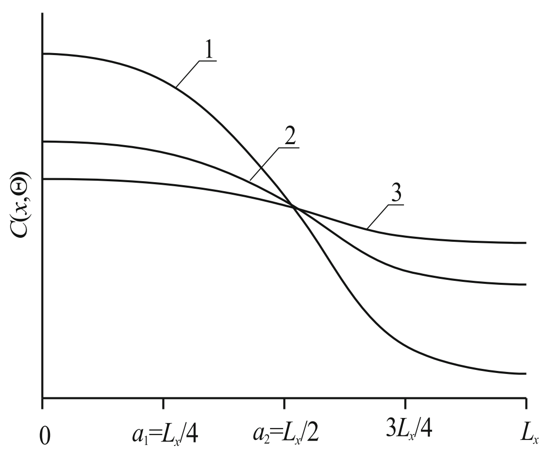


**Fig. 8** Distribution of dopant in heterostructure with three layers (substrate and two epitaxial layers) for different values of annealing time. Values of annealing time are: $\Theta = 0.2\,L^2/D_0$, $\Theta = 0.4\,L^2/D_0$ and $\Theta = 0.7\,L^2/D_0$

coefficients in layers of H and values of annealing time. The figures show, that increasing of difference between values of diffusion coefficient gives us possibility to increase sharpness of *p*–*n* junction. With increasing of annealing time homogeneity of dopant distribution increases, but sharpness of *p*–*n* junction decreases. Existence of interface between layers of H gives us possibility to increase sharpness of *p*–*n* junction after annealing with appropriate continuance.

To obtain compromise between increasing of homogeneity of dopant distribution and increasing sharpness of *p*–*n* junction let us consider a recently introduced criterion (Pankratov 2005, 2010) for optimization of annealing time. Framework the criterion let us approximate spatial distribution of dopant by step-wise function $\psi(x, y, z)$ with not yet determined height and width (see Fig. 9). The height,

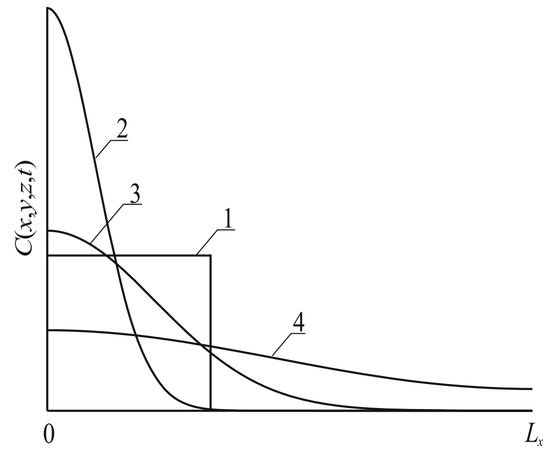


**Fig. 9** Spatial distributions of dopant in H for diffusion doping. *Curve 1* is idealized distribution of dopant. *Curves 2–4* are real distributions of dopant for different values of annealing time (increasing of number of curves corresponds to increasing of value of annealing time). Values of annealing time are: $\Theta = 0.01\,L^2/D_0$, $\Theta = 0.1\,L^2/D_0$ and $\Theta = L^2/D_0$

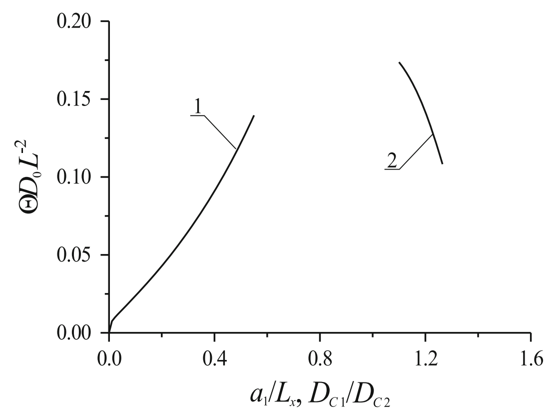


**Fig. 10** Dependences of dimensionless optimal annealing time of dopant in H on several parameters. *Curve 1* is dependence of annealing time on ratio $a_1/L_x$ for $D_1 = D_2 = D_S$. Dependence of annealing time on ratio $a_2/L_x$ is analogous to above dependence. *Curve 2* is dependence of annealing time on ratio $D_1 = D_S$ for $a_1/L_x = 1/2$. Dependence of annealing time on ratio $D_2 = D_S$ is analogous to above dependence

width and optimal annealing time we obtain by minimization of the following mean-squared error:

$$U = \frac{1}{\Theta L_x L_y L_z} \int_0^{\Theta} \int_0^{L_x} \int_0^{L_y} \int_0^{L_z} \left[C(x,y,z,t) - \psi(x,y,z)\right] \mathrm{d}z\mathrm{d}y\mathrm{d}x\mathrm{d}t.$$

Dependences of optimal annealing time on several parameters are presented in Fig. 10.

## Conclusion

In this paper an approach has been elaborated to manufacture more compact planar field-effect transistor in semiconductor heterostructure. The approach is based on using native inhomogeneities of the heterostructure and optimization of technological process.

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## Appendix

The equations and conditions for the functions $C_{ij}(x, y, z, t)$ ($i \geq 0$ and $j \geq 0$) are:

$$\frac{\partial C_{00}(x,y,z,t)}{\partial t} = D_{0L}\frac{\partial^2 C_{00}(x,y,z,t)}{\partial x^2} + D_{0L}\frac{\partial^2 C_{00}(x,y,z,t)}{\partial y^2} + D_{0L}\frac{\partial^2 C_{00}(x,y,z,t)}{\partial z^2}$$

$$\frac{\partial C_{i0}(x,y,z,t)}{\partial t} = D_{0L}\left[\frac{\partial^2 C_{i0}(x,y,z,t)}{\partial x^2} + \frac{\partial^2 C_{i0}(x,y,z,t)}{\partial y^2} + \frac{\partial^2 C_{i0}(x,y,z,t)}{\partial z^2}\right] + D_{0L}\left\{\frac{\partial}{\partial x}\left[g_L(x,y,z,T) \times \frac{\partial C_{i-10}(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[g_L(x,y,z,T)\frac{\partial C_{i-10}(x,y,z,t)}{\partial y}\right] + \frac{\partial}{\partial z}\left[g_L(x,y,z,T)\frac{\partial C_{i-10}(x,y,z,t)}{\partial z}\right]\right\},\ i \geq 1;$$

$$\frac{\partial C_{01}(x,y,z,t)}{\partial t} = D_{0L}\left[\frac{\partial^2 C_{01}(x,y,z,t)}{\partial x^2} + \frac{\partial^2 C_{01}(x,y,z,t)}{\partial y^2} + \frac{\partial^2 C_{01}(x,y,z,t)}{\partial z^2}\right] + D_{0L}\left\{\frac{\partial}{\partial x}\left[\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)} \times \frac{\partial C_{00}(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{00}(x,y,z,t)}{\partial y}\right] + \frac{\partial}{\partial z}\left[\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{00}(x,y,z,t)}{\partial z}\right]\right\};$$

$$\frac{\partial C_{02}(x,y,z,t)}{\partial t} = D_{0L}\left[\frac{\partial^2 C_{02}(x,y,z,t)}{\partial x^2} + \frac{\partial^2 C_{02}(x,y,z,t)}{\partial y^2} + \frac{\partial^2 C_{02}(x,y,z,t)}{\partial z^2}\right] + D_{0L}\left\{\frac{\partial}{\partial x}\left[\frac{C_{00}^{\gamma-1}(x,y,z,t)}{P^{\gamma}(x,y,z,T)} \times C_{01}(x,y,z,t)\frac{\partial C_{00}(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[C_{01}(x,y,z,t)\frac{C_{00}^{\gamma-1}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{00}(x,y,z,t)}{\partial y}\right] + \frac{\partial}{\partial z}\left[\frac{C_{00}^{\gamma-1}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}C_{01}(x,y,z,t)\frac{\partial C_{00}(x,y,z,t)}{\partial z}\right]\right\} + D_{0L}\left\{\frac{\partial}{\partial x}\left[\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{01}(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{\partial C_{01}(x,y,z,t)}{\partial y}\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\right] + \frac{\partial}{\partial z}\left[\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{00}(x,y,z,t)}{\partial z}\right]\right\};$$

$$\frac{\partial C_{11}(x,y,z,t)}{\partial t} = D_{0L}\left[\frac{\partial^2 C_{11}(x,y,z,t)}{\partial x^2} + \frac{\partial^2 C_{11}(x,y,z,t)}{\partial y^2} + \frac{\partial^2 C_{11}(x,y,z,t)}{\partial z^2}\right] + D_{0L}\left\{\frac{\partial}{\partial x}\left[g_L(x,y,z,T)\frac{\partial C_{01}(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[g_L(x,y,z,T)\frac{\partial C_{01}(x,y,z,t)}{\partial y}\right] + \frac{\partial}{\partial z}\left[g_L(x,y,z,T)\frac{\partial C_{01}(x,y,z,t)}{\partial z}\right]\right\} + D_{0L}\left\{\frac{\partial}{\partial x}\left[C_{10}(x,y,z,t)\frac{C_{00}^{\gamma-1}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{00}(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[C_{10}(x,y,z,t)\frac{C_{00}^{\gamma-1}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{00}(x,y,z,t)}{\partial y}\right] + \frac{\partial}{\partial z}\left[C_{10}(x,y,z,t)\frac{C_{00}^{\gamma-1}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{00}(x,y,z,t)}{\partial z}\right]\right\} + D_{0L}\left\{\frac{\partial}{\partial x}\left[\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{10}(x,y,z,t)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{10}(x,y,z,t)}{\partial y}\right] + \frac{\partial}{\partial z}\left[\frac{C_{00}^{\gamma}(x,y,z,t)}{P^{\gamma}(x,y,z,T)}\frac{\partial C_{10}(x,y,z,t)}{\partial z}\right]\right\};$$

$$\left.\frac{\partial Cij(x,y,z,t)}{\partial x}\right|_{x=0} = 0, \left.\frac{\partial C_{ij}(x,y,z,t)}{\partial x}\right|_{x=L_x} = 0, \left.\frac{\partial C_{ij}(x,y,z,t)}{\partial y}\right|_{y=0} = 0, \left.\frac{\partial C_{ij}(x,y,z,t)}{\partial y}\right|_{y=L_y} = 0, \left.\frac{\partial C_{ij}(x,y,z,t)}{\partial z}\right|_{z=0} = 0, \left.\frac{\partial C_{ij}(x,y,z,t)}{\partial x}\right|_{z=L_z} = 0,\ i \geq 0,\ j \geq 0; C_{00}(x,y,z,0) = f_C(x,y,z), C_{ij}(x,y,z,0) = 0, i \geq 1, j \geq 1.$$

Solutions of the equations with account boundary and initial conditions could be written as:

$$C_{00}(x,y,z,t) = -2\sum_{i=1}^{\infty}\int_0^t enC(-\tau)\int_0^{L_x} s_n(u)\int_0^{L_y} c_n(v)\int_0^{L_z} c_n(w)\left[F_{nC} + \frac{D_{CS}(u,T)}{\bar{V}kT}\frac{\partial\mu(u,v,w,\tau)}{\partial u}\right] \mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$\times \pi e_{nC}(t)\frac{C_n(x,y,z)}{L_x^2 L_y L_z} - 2\pi\sum_{i=1}^{\infty} n\frac{C_n(x,y,z)}{L_x L_y^2 L_z}\int_0^t e_{nC}(-\tau)\int_0^{L_x} c_n(u)\int_0^{L_y} s_n(v)\int_0^{L_z}\left[F_{n\Phi_I} + \frac{D_{CS}(u,T)}{\bar{V}kT}\frac{\partial\mu(u,v,w,\tau)}{\partial v}\right]$$

$$\times c_n(w)\,\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau e_{nC}(t) - 2\pi\sum_{i=1}^{\infty} e_{nC}(t)\frac{C_n(x,y,z)}{L_x L_y L_z^2}\int_0^t e_{nC}(-\tau)\int_0^{L_x} c_n(u)\int_0^{L_y} c_n(v)\int_0^{L_z} s_n(w)\left[\frac{\partial\mu(u,v,w,\tau)}{\partial w}\right.$$

$$\left.\times\frac{D_{CS}(u,T)}{\bar{V}kT} + F_{nC}\right]\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau n.$$

Here $e_{nC}(t) = \exp\left[-\pi^2 \mathrm{n}^2 \mathrm{D}_{0\mathrm{L}}\mathrm{t}\left(\frac{1}{\mathrm{L}_\mathrm{x}^2} + \frac{1}{\mathrm{L}_\mathrm{y}^2} + \frac{1}{\mathrm{L}_\mathrm{z}^2}\right)\right]$, $F_{nC} = \int_0^{L_x} c_n(u)\int_0^{L_y} c_n(v)\int_0^{L_z} c_n(w) f_C(u,v,w)\,\mathrm{d}w\mathrm{d}v\mathrm{d}u$;

$$C_{i0}(x,y,z,t) = -2\pi\sum_{i=1}^{\infty} n\int_0^t e_{nC}(-\tau)\int_0^{L_x} s_n(u)\int_0^{L_y} c_n(v)\int_0^{L_z} c_n(w) g_L(u,T)\frac{\partial C_{i-10}(u,v,w,\tau)}{\partial u}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$\times e_{nC}(t)\frac{C_n(x,y,z)}{L_x^2 L_y L_z} - 2\pi\sum_{i=1}^{\infty} n\int_0^t e_{nC}(-\tau)\int_0^{L_x} c_n(u)\int_0^{L_y} s_n(v)\int_0^{L_z} c_n(w) g_L(u,T)\frac{\partial C_{i-10}(u,v,w,\tau)}{\partial v}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$\times e_{nC}(t)\frac{C_n(x,y,z)}{L_x L_y^2 L_z} - 2\pi\sum_{i=1}^{\infty} n\int_0^t e_{n\Phi_I}(-\tau)\int_0^{L_x} c_n(u)\int_0^{L_y} c_n(v)\int_0^{L_z} s_n(w) g_L(u,T)\frac{\partial C_{i-10}(u,v,w,\tau)}{\partial u}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$\times e_{nC}(t)\frac{C_n(x,y,z)}{L_x L_y^2 L_z}, i \geq 1;$$

$$C_{01}(x,y,z,t) = -2\pi\sum_{i=1}^{\infty}\int_0^t e_{nC}(-\tau)\int_0^{L_x} s_n(u)\int_0^{L_y} c_n(v)\int_0^{L_z} c_n(w)\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{00}(u,v,w,\tau)}{\partial u}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$\times n e_{nC}(t)\frac{C_n(x,y,z)}{L_x^2 L_y L_z} - 2\pi\sum_{i=1}^{\infty} e_{nC}(t)\frac{C_n(x,y,z)}{L_x L_y^2 L_z}\int_0^t e_{nC}(-\tau)\int_0^{L_x} c_n(u)\int_0^{L_y} s_n(v)\int_0^{L_z} c_n(w)\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}$$

$$\times n\frac{\partial C_{00}(u,v,w,\tau)}{\partial v}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau - 2\pi\sum_{i=1}^{\infty} e_{nC}(t)\frac{C_n(x,y,z)}{L_x L_y L_z^2}\int_0^t e_{nC}(-\tau)\int_0^{L_x} c_n(u)\int_0^{L_y} c_n(v)\int_0^{L_z} s_n(w)$$

$$\times n\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{00}(u,v,w,\tau)}{\partial w}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau;$$

$$C_{02}(x,y,z,t) = -2\pi\sum_{i=1}^{\infty}\int_0^t e_{nC}(-\tau)\int_0^{L_x} s_n(u)\int_0^{L_y} c_n(v) n\int_0^{L_z} c_n(w)\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{01}(u,v,w,\tau)}{\partial u}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau e_{nC}(t)\frac{C_n(x,y,z)}{L_x^2 L_y L_z}$$

$$- 2\pi\sum_{i=1}^{\infty} e_{nC}(t)\frac{C_n(x,y,z)}{L_x L_y^2 L_z} n\int_0^t e_{nC}(-\tau)\int_0^{L_x} c_n(u)\int_0^{L_y} s_n(v)\int_0^{L_z} c_n(w)\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{01}(u,v,w,\tau)}{\partial v}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_xL_yL_z^2}\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}s_n(w)\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{01}(u,v,w,\tau)}{\partial w}\,\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_x^2L_yL_z}\int_0^t e_{nC}(-\tau)\int_0^{L_x}s_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}c_n(w)C_{01}(u,v,w,\tau)\frac{C_{00}^{\gamma-1}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{00}(u,v,w,\tau)}{\partial u}\,\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_xL_y^2L_z}\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\int_0^{L_y}s_n(v)\int_0^{L_z}c_n(w)C_{01}(u,v,w,\tau)\frac{C_{00}^{\gamma-1}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{00}(u,v,w,\tau)}{\partial v}\,\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau$$

$$-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_xL_yL_z^2}\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}s_n(w)C_{01}(u,v,w,\tau)\frac{C_{00}^{\gamma-1}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{00}(u,v,w,\tau)}{\partial w}\,\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau;$$

$$\begin{aligned}C_{11}(x,y,z,t)={}&-2\pi\sum_{i=1}^{\infty}\int_0^t e_{nC}(-\tau)\int_0^{L_x}s_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}c_n(w)\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{01}(u,v,w,\tau)}{\partial u}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau\\
&\times ne_{nC}(t)\frac{C_n(x,y,z)}{L_x^2L_yL_z}-2\pi\sum_{i=1}^{\infty}e_{nC}(t)\frac{C_n(x,y,z)}{L_xL_y^2L_z}\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\int_0^{L_y}s_n(v)\int_0^{L_z}c_n(w)\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\\
&\times n\frac{\partial C_{01}(u,v,w,\tau)}{\partial v}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_xL_yL_z^2}\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}s_n(w)\\
&\times\frac{C_{00}^{\gamma}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{01}(u,v,w,\tau)}{\partial w}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_x^2L_yL_z}\int_0^t e_{nC}(-\tau)\int_0^{L_x}s_n(u)\int_0^{L_y}c_n(v)\\
&\times\int_0^{L_z}c_n(w)C_{10}(u,v,w,\tau)\frac{C_{00}^{\gamma-1}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{00}(u,v,w,\tau)}{\partial u}\,\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_xL_y^2L_z}\\
&\times\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\int_0^{L_y}s_n(v)\int_0^{L_z}c_n(w)C_{10}(u,v,w,\tau)\frac{C_{00}^{\gamma-1}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\frac{\partial C_{00}(u,v,w,\tau)}{\partial v}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau\\
&-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_xL_yL_z^2}\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}s_n(w)C_{10}(u,v,w,\tau)\frac{C_{00}^{\gamma-1}(u,v,w,\tau)}{P^{\gamma}(u,v,w,T)}\\
&\times\frac{\partial C_{00}(u,v,w,\tau)}{\partial w}\,\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_x^2L_yL_z}\int_0^t e_{nC}(-\tau)\int_0^{L_x}s_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}c_n(w)\\
&\times g_L(u,v,w,T)\frac{\partial C_{01}(u,v,w,\tau)}{\partial u}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_xL_y^2L_z}\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\\
&\times\int_0^{L_y}s_n(v)\int_0^{L_z}c_n(w)g_L(u,v,w,T)\frac{\partial C_{01}(u,v,w,\tau)}{\partial v}\,\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau-2\pi\sum_{i=1}^{\infty}ne_{nC}(t)\frac{C_n(x,y,z)}{L_xL_yL_z^2}\\
&\times\int_0^t e_{nC}(-\tau)\int_0^{L_x}c_n(u)\int_0^{L_y}c_n(v)\int_0^{L_z}s_n(w)g_L(u,v,w,T)\frac{\partial C_{01}(u,v,w,\tau)}{\partial w}\mathrm{d}w\mathrm{d}v\mathrm{d}u\mathrm{d}\tau.\end{aligned}$$

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